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An investigation of the cost and performance of a solar-powered LED light designed as an alternative to candles in Zambia: A project case study

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ABSTRACT

The economic, health, and environmental costs of kerosene, candles, and other fuel-based lighting are well-documented. As a result of efforts by the World Bank and other organizations, numerous lighting products incorporating solar photovoltaic and light-emitting diodes (LEDs) have been introduced in Sub-Saharan Africa. The category of solar portable lights is increasingly popular, in part because the lower retail price of these lights can make them more affordable to lower-income households. The UC Davis Lighting the Way Zambia project sought to explore the minimum costs and performance requirements for a solar portable light targeting candle and kerosene users in Zambia. This paper discusses the product design process, including the establishment of performance requirements and metrics, as well as a cost-optimization exercise used to evaluate key electronic components. The cost structure of the final design is presented with end-user costs and actual manufacturing costs. The results suggest that an 18-lumen solar portable light with a 4-h run time would meet many users' needs and can be manufactured for less than US$9 per unit, with a cost of $0.34 per 1000 l m-h and a payback period of around 6 months.

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1. Introduction

An estimated 1.5 billion people (74% of sub-Saharan Africa) do not have access to electricity, and must rely on fuel-based lighting—kerosene, candles, wood, and other biomass [22]. Fuel-based lighting carries high costs for end-users worldwide, including: *economic costs* – $38 billion a year, or an average of $77/year per household; *health/safety costs* – thousands suffer from indirect effects of combustion including smoke inhalation, house fires, and burns; and *environmental costs* – burning of lighting fuels releases an estimated 190 million metric tons CO_2 equivalent [14]. The most common fuel, kerosene, is an inefficient source of energy for illumination, such that lower-income households not only pay significant amounts for the kerosene that they use, but the lighting "service" they receive—defined as the amount and quality of illumination—is significantly lower as compared to electrified households or even propane lanterns. For example, users of basic kerosene lamps pay 150 times more per useful unit of lighting than users of grid-connected compact fluorescents [16], and approximately 8 times more than the solar portable light developed in this study. In Africa, population growth is expected to outstrip growth of the electrical grid infrastructure, meaning that the current unelectrified population of 110 million is projected to increase to 120 million by 2015 [10]. The mounting pressures of population growth and environmental sustainability make fuel-based lighting an important issue to address.

This paper begins with a brief overview of solar photovoltaic technology in the developing world, followed by background on the project and Zambian demographics. The next section covers the research into customer preferences, performance requirements, and cost constraints. The core of the paper describes how these performance requirements were translated into a product design, and how an optimization algorithm was used to determine the best configuration based on component and manufacturing costs. The paper concludes with a detailed analysis of the manufacturing costs and customer costs, with some thoughts on the potential for cost decreases in the future.

1.1. Solar technology as an alternative

For sub-Saharan Africa and other regions that receive substantial solar radiation year-round, off-grid lighting systems that use solar photovoltaic (PV) technology are considered a promising alternative to fuel-based lighting. Solar-powered lights can be used anywhere there is sunlight, they charge with use of the solar panel during daylight hours, and their operation creates no soot, emissions, or direct fire risks. For these reasons solar PV technology has been widely promoted as a cost-effective means to provide lighting services for rural areas where it is too expensive to extend the electricity grid. More recently, concerns over greenhouse gas emissions have increased interest and promotion of solar technology as a clean, renewable resource, especially when it replaces the use of fossil fuels such as kerosene [23]. Importantly, the benefits of solar PV systems are valued differently among stakeholders. End-users are most interested in the financial savings and performance improvements over fuel-based lighting, and it is typically only international Non Governmental Organizations (NGOs), regulators, or private sector investors that place direct value on the environmental benefits [23].

1.2. Solar home systems

The most widely promoted category of solar technology for off-grid lighting use is the solar home system (SHS). SHSs have been used for decades, with an estimated 1.3 million systems distributed in developing countries [18]. SHSs typically range from 20–100 W, and at the higher power levels can support other devices in addition to lights, such as TVs, radios, or mobile phone chargers. SHSs typically comprise one or more solar PV panels, a charge controller, a battery, and an inverter for AC loads.

Proponents of SHSs promote the cost-effectiveness of these systems, often using "levelized cost" or "total cost of ownership" to show that the full lifetime costs of the system per energy service provided are low, due to the negligible operating costs. However, despite widespread funding and subsidies from international development agencies, NGOs, and local governments, market penetration of SHSs has been limited [6]. Primary barriers to adoption include the high initial investment cost (typically $200–$600 retail price) and the technical expertise needed for professional installation and maintenance [18,19,23]. The high initial investment cost requires financing, subsidies, donations, or some combination of these. In countries such as Bangladesh, with its extensive network of microfinance institutions, SHS adoption has exceeded projections [5]. But in regions and communities where appropriate credit mechanisms are not readily available, SHSs are less accessible [12].

1.3. Solar portable lights

A growing number of smaller off-grid lighting products, often referred to as "solar lanterns", "micro" or "pico" solar lights, are currently entering the market. The authors follow the recent convention of the Lighting Africa Development Marketplace and refer to this category as "solar portable lights" or SPLs [10]. These systems typically use less than 10 W of power, cost $20–$70, and are self-contained products that emulate lanterns, torches (flashlights), or desk lamps in size and form factor. Compared to SHSs, solar portable lights are generally less robust, with lower service capacity, lower efficiencies, and shorter product life spans. However, the lower retail price of solar portable lights, around 10% of a SHS, makes them more accessible to a broader segment of unelectrified households. Therefore while less cost-efficient compared to the larger SHS or community-scale solar systems, solar portable lights can still offer significant cost, performance, and health benefits to the end user switching from fuel-based lighting. Table 1 provides a comparison between the costs and features of SHSs and SPLs.

Demand for lower-cost options is reflected in positive reactions to SPL product testing with kerosene users in sub-Saharan Africa [15,21,9] and, more tellingly, in growing sales figures for those organizations with established products and distribution outlets [3]. However, even at a cost of $20–$50 per SPL, many poor still cannot pay full retail price without some kind of financing. So despite having an upfront cost that is an order of magnitude lower than with SHS, solar portable lights that require financing face a significant barrier to widespread adoption among many low-income households.

Table 1
Comparison of SHS and solar portable lights.[a]

System	Upfront cost (USD)	Lighting service	Other services?	Typical product warranty	Requires technical installation	Requires maintenance
SHS	$200–$600	450–3600 lm	Potentially	3–20 years	Yes	Yes
Solar portable lights	$11–$65	10–70 lm	No	0–1 years	No	No

[a] SHS estimates are based on data from a major SHS manufacturer in Bangladesh. The warranties offered for these SHSs are: 3 years for charge controller, 5 years for battery, and 20 years for solar PV. SPL estimates based on [9] market report and analysis of manufacturer specifications and warranties.

1.4. Project background

This project was initiated as part of the World Bank's Lighting Africa Development Marketplace (LADM) program, launched in 2008 with a goal of spurring innovation and growth in the off-grid lighting industry [7]. The UC Davis team received funding from LADM to design, build and distribute an affordable portable solar light to compete with fuel-based lighting in Zambia. The focus of the project was to develop a lighting alternative that could be purchased by kerosene and candle users *without subsidy or financing*. The design process was therefore framed by the focus on an affordable retail cost, and understanding how to meet users' minimum functional, aesthetic, and performance requirements within that cost structure. The project team conducted research in different target communities in Zambia, including urban, peri-urban, and rural communities, to better understand user behavior and preferences with lighting. The final design tested positively with users, was manufactured in an initial production run in 2011, and will begin distribution in 2012. Although working specifically with the Zambian market, this paper focuses on development and production costs that will be relevant regardless of where a product is eventually sold. It is worth noting, however, that factors such as transportation infrastructure, governmental regulation, and import tariffs/taxes can all have significant effects on final retail prices.

2. Research and product design process

To understand the requirements for designing the solar-powered light the project team spent time with kerosene and candle users in Zambia to learn about current behavior, perceptions of existing lighting, and lighting expenditures, both in terms of initial investment costs and ongoing operating expenses. Methods included focus groups, one-on-one interviews, and in-person surveys. UC Davis and Zambian team members conducted the research in urban, peri-urban, and rural communities around Lusaka. Rural communities involved included Kanakantapa, Kafue, Chilanga, and Chongwe; peri-urban communities of Lusaka included Chunga, George, Desai, Chawama, Kanyama, and Kalikiliki.

2.1. Identifying customers

Zambia has a population of almost 12 million, more than half of which lives in rural areas. While an estimated 18% of the total population has access to grid electricity, only 2% of those living in rural areas have grid access [8]. Therefore, a core target customer segment was the rural communities that have little chance of ever having electricity extended to their area. Another customer profile was determined to be households living in a peri-urban community, on the outskirts of the urban core. These communities, called "compounds" in Zambia, are often unplanned or informal settlements, and while geographically close to the city center, are generally excluded from city services such as water, sewer, and electricity.

Table 2
Key performance specifications of final design.

Specification	Rationale
Provides a minimum 15 lm of usable light	Equal to or slightly better than light output of kerosene wick lantern or candle
Runs for at least 4 h on a charge	Majority of users indicated nightly usage of 3–4 h for kerosene lantern or candle
Re-charges in one day	Required for daily use; based on Zambia's latitude and average of 5.5 h peak sun daily
Includes smart charge protection: automatic low-voltage shut-off to prevent damage to battery, overcharge protection, sunlight-sensor to prevent accidental draining of battery if light is left on	Charge protection increases battery life and helps to differentiate product from cheap imports that are spoiling the market
Uses standard, widely available AA battery type	Enables users to replace the battery themselves without tying them to proprietary technology

Average income in Zambia is approximately US$150 per month, with urban incomes typically slightly higher than rural. The majority of unelectrified households across locations in Zambia use candles (79%) instead of kerosene (14%) for lighting. This contrasts sharply with Kenya, which is more representative of sub-Saharan African countries in general, where 5% of households use candles and 67% use kerosene. For Zambian users, household expenditures were similar whether candles or kerosene were the main source of fuel [9,10]. The team investigated whether candle users and kerosene users reported different behavior or preference in regards to lighting, and found no significant differences that would impact our product design [20].

2.2. Defining performance requirements

The initial field research sought to determine the basic features and performance of the product, focusing on illumination, runtime, and battery life, as summarized in Table 2. Of these, illumination was considered the most important performance criterion to define. Illumination is typically measured in one of two ways, based on the type of light and its application: for task lights, such as torches or desk lamps, light is often measured in lux, the amount of visible light that contacts a surface at a specified distance. For example, a desk lamp may provide 20 lx at 1 m from the lamp. For ambient lights, output is often measured in lumens the total visible light being emitted by a lamp in all directions. The relationship between these can be expressed by the form: $1\ \text{lx} = 1\ \text{lm/meter}^2$. Because the final design was an ambient ceiling light, measurements were based on lumens.

What constitutes "acceptable" light levels depends on many variables, including the type of task being performed, environmental conditions, eyesight of the user, and more [1]. Therefore it was decided that a typical lighting product—a candle or basic kerosene lamp—would serve as a baseline indicator of minimally

acceptable light output. Laboratory measurements for typical kerosene lamps show that light output can vary significantly based on lamp type, wick size, and quality of kerosene, but has been measured at approximately 8 lm for a basic wick lamp [14]. The team assumed that any new product, especially one that featured solar and LED technology, would have to outperform existing lighting options, leading to a minimum acceptable light output for the product defined at 15 lm.

The required daily runtime determined product charging and energy storage requirements. Our research supported other studies in Zambia indicating that average nightly usage of candles and kerosene is about 3 h [4,9]. Again using the current kerosene and candle usage patterns as a minimum baseline, we established 4 h as the required nightly runtime for the product. This meant that the product needed the capacity to sufficiently charge the battery in one day to provide 4 h of runtime. The daily average peak sun hours for Zambia were estimated at 5.5 h [17].[1]

Almost all research participants were familiar with using batteries in electronic devices, and many inquired about the type of battery that would be used, how long it would last, and whether it could be replaced. There was clear customer familiarity with battery charging issues, particularly related to low-quality batteries and imported LED products. Respondents reported that low-cost lights from China, typically non-solar rechargeable LED torches, tend to experience problems with battery charging and circuit failure, leading to customer skepticism [20]. Other research [16,10] supports the idea that low-quality products are currently spoiling the market in sub-Saharan Africa. Therefore the UC Davis project team decided that the design should include a ‘‘smart’’ circuit and charging function, which protects the battery from overcharging, deep discharge, and accidental discharge. This functionality prolongs battery life, and because replacement batteries constitute the only operating cost of the product, has a significant effect on total cost of ownership.

2.3. Determining cost constraints

Analyzing lighting expenditures from the customer perspective was critical in order to understand the cost constraints for the new design. For kerosene and candles, average household expenditures in five sub-Saharan countries surveyed by the World Bank ranged from $2.63–$4.64 per month; these expenditures represent ‘‘operating costs’’ and do not include the initial investment cost of purchasing a lantern [8]. The authors' research in Zambia indicated monthly household operating costs ranging from $4–$8 per month, with almost no difference between candle users and kerosene users (self-reported expenditures ranged from $1–$8, with 73% of respondents ($n=52$) spending between $4–$8 per month on kerosene and/or candles) [20].

Upfront costs for kerosene-based lighting products include the purchase price of the kerosene lamp and wick, with the main operating expense being kerosene. Kerosene hurricane lamps with glass enclosures cost $2–$5 in Zambia, while basic kerosene wick lamps—typically fashioned from tin cans or other discarded material—can be purchased for less than $0.25. Candles are self-contained with the upfront cost being equal to the operating cost. Standard candles cost 700–1000 kwacha (Kw), or approximately US$0.14–$0.20 (per June 2009 rate of Kw5100 per US$1), and typically burn for 4 h or about two nights. In Zambia most households report multiple instances of either kerosene lamps or candles, with one in each room being lighted. Some respondents reported carrying a kerosene lamp or candle from room to room, though this was less common.

While kerosene and candles have relatively high operating costs, these expenditures can be broken down into affordable increments (i.e., individual candles, or 100 mL of kerosene) that can be purchased as needed, similar to how small sachets of detergent or a few minutes' worth of mobile phone talk time are purchased in these countries. Compared to solar-powered lights, the barrier to entry for kerosene or candles is low enough to make them accessible to even the very poor.

In interviews and focus groups conducted by the project team, most users of kerosene and candles were aware of the high operating costs they pay compared to those with grid electricity. They also understood that solar-powered lights are cheaper to use compared to kerosene or candles, but they could not afford such a large initial investment. Indeed, solar technology offers negligible operating costs, and lower total cost of ownership (TCO) compared to kerosene or candles, but upfront cost is the most important measure of affordability for low-income households. This was supported by respondents in peri-urban housing compounds outside of Lusaka, where many said they were able to pay more than $2.50, some said they were able to pay more than $5, but few said they were able to pay more than $10 without a payment plan [20].

3. Final design characteristics

Because the underlying technology used in solar portable lights is well understood, the design challenge was to first determine an optimal form factor, and secondly to select the combination of components that most effectively produced the required performance within the cost constraints. This section includes discussion of the final product form factor and features, followed by an optimization exercise that was used to select the best combination of key components.

3.1. Form factor and general components

Based on input from the focus groups and interviews, the project team decided that ambient lighting could serve more needs than focused task lighting (e.g., torch or desk lamp) and therefore have a more compelling value proposition for the customer. In terms of form factor, it was determined that a hanging overhead light could maximize the usable light emitted due to virtually 100% of the light being directed down toward the user, mimicking the basic ‘‘bulb-on-a-wire’’ ceiling lights common to many electrified homes in Zambia. This configuration is supported by modern LED designs, where an angle of illumination of 120 degrees is common.

The final design (Fig. 1) comprises a small solar panel, to be hung on the roof or in a window, connected with a 4-m wire to the light body. The length of wire and installation requirements were validated against common house dimensions in Zambia, as well as by a building engineer for a large NGO focused on construction of low-income housing in compounds outside of Lusaka. While the product can perform as a conventional hanging ceiling light, the wire has an inline connector (standard DC plug of a type used on many consumer electronics) so that the light body can be disconnected from the solar panel and used in another room or as a mobile light. The team had sought to distinguish the product from a torch due to reported customer association of the

[1] Based on Lusaka's longitude and latitude. Peak sun hours mean the equivalent number of hours per day when solar irradiance averages 1000 w/m^2. Put differently, 5.5 peak sun hours is equal to an average of 5500 W-h/m^2 per day. Importantly, while there is seasonal variation of insolation in Lusaka, the month with the least, June, still averages 5.2 peak sun hours. Estimate based on NASA Surface meteorology and Solar Energy (SSE) data; assumes horizontal inclination (‘‘flat plate'').

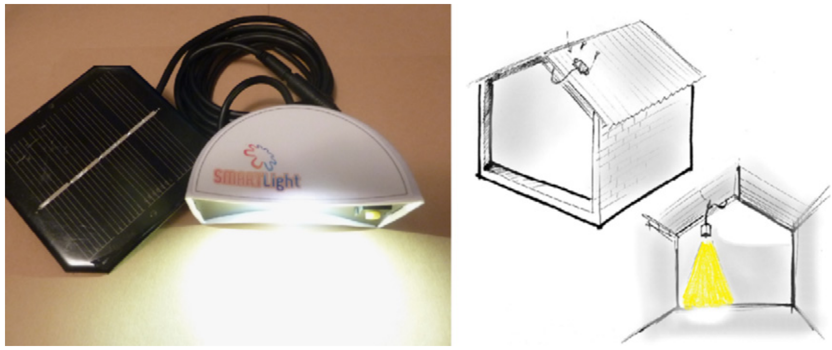


Fig. 1. Final product: a household light that mimics ceiling lights in grid-powered homes.

Table 3
Key considerations in the product design.

Element	Considerations
Solar cell	Must deliver sufficient power to charge 1.2 V battery in 5.5 h of average peak sun hours in Zambia Resistance in wiring can be significant at low voltages and must be accounted for Amorphous silicon typical for this size is cheaper but less efficient than polycrystalline Epoxy-coated solar cells yellow with exposure to sun, decreasing efficiency within 2 years; PET-laminated lasts longer but has higher cost Glass cover and aluminum frame extend cell lifespan, but have higher cost
Battery	Charging capacity should be oversized from daily requirements in order to provide a buffer for cloudy days, which extends the working life of the battery Battery types evaluated over cost, energy density, deep discharge tolerance, self-discharge rate, toxicity and other parameters; nickel-metal hydride (NiMh) was deemed most appropriate AA form factor is nonproprietary, available globally Single battery avoids user uncertainty in replacement Battery lifespan > 50% capacity after 500 cycles
LED	Efficacy (lumens-per-watt) is significant factor in overall product performance LEDs typically designed to run in specific power range Lower-quality LEDs can have significant variations in performance and color[a] Color temperature can be an issue cooler white is cheaper than warm white for the same light output; user preferences may depend on familiarity with fluorescent lighting
Circuitry	Energy-efficient design is critical for low-power application Selection of LED driver integrated circuit changes efficiency Circuit should deliver constant current for optimal LED operation[b] Surface area and complexity (i.e., layers) of printed circuit board (PCB) impact costs Surface-mount components are cheaper for automated assembly, but may preclude manual assembly Switch quality is important, especially given various environmental conditions
External wiring	Sufficiently small resistance for low-power DC current Molded connector with appropriate grab strength and durability
Case and packaging	Injection-molded plastic housing with removable cover Simplified geometric case design has lower tooling cost, additionally this minimizes material usage for lower per-unit costs and shipping costs Basic packaging minimizes material for lower per-unit costs and shipping costs Simple cardboard box with paper insert

[a] See [15].
[b] Ibid.

torch form factor with lower-price and lower-quality products [9]. However, in focus groups there were repeated requests for mobility, which were addressed by the addition of the inline connector. The single battery is a rechargeable NiMh AA, a common, non-proprietary battery type that can be replaced by the user. A simple on-off switch controls operation; there are no variable lighting modes. The lamp "bulb" is a high-efficacy surface-mount LED.

In this study these components were grouped into six basic "elements" that are common across many modern solar portable lights. These are: (1) solar cell for converting sunlight to electrical energy, (2) battery for energy storage, (3) LED lamp for illumination, 4) electronic circuitry for controlling operation, (5) external wiring, and (6) case and packaging. Table 3 indicates the key considerations for each element.

3.2. System cost optimization: methodology

In general for a given element, such as the LED, an increase in performance or efficiency comes with an increase in cost (for example, see Fig. 2). However, these increases are not always linear, and due to the dependencies and specific interactions between components, it is not always apparent which element combination will offer the most cost-effective performance for the product as a whole. Thus the project team performed an optimization exercise to determine the most cost-effective combination of elements.

It should be noted that due to multiple specifications of each individual component, and differences in quality that may or may not be reflected in the measured performance, it was not within the scope of this exercise to incorporate all individual component characteristics into the analysis. For example, one type of wiring

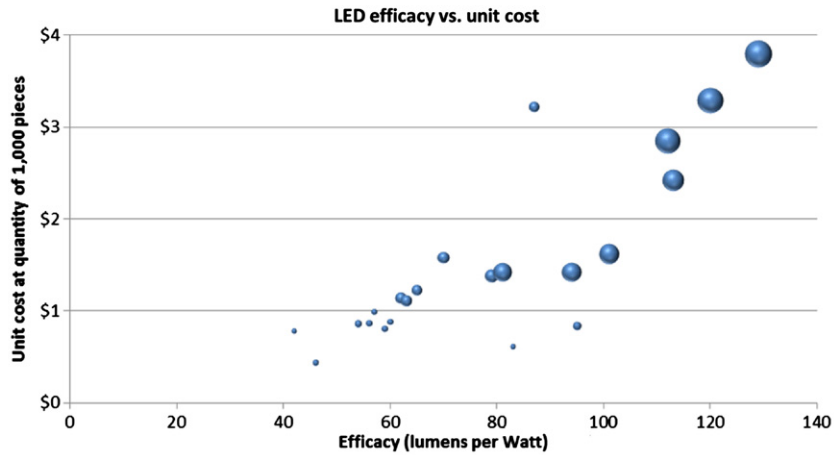


Fig. 2. LED efficacy and cost for specific power range. Bubble size indicates max lumens of LED (higher power output typically correlates to higher lumen output).

Table 4
Elements tested in optimization exercise.

Element	Variable	Units	Values tested		
PV cell	Current	Amps	0.25	0.3	0.35
Wiring	Resistance	Ohms	0.67	0.42	0.27
Battery	Capacity	Watt-hours	1.8	2.04	2.4
LED	Efficacy	Lumens/Watt	46	60	90

may have a more durable plastic sheath, or a certain type of solar panel may have better solder pads on the back for attaching the wiring. While these kinds of features play a role in ultimate part selection, they were not considered in this analysis.

To conduct the optimization, the team first defined the basic circuit parameters that would be held as constants, the most important being battery type and LED driver (the LED driver is the integrated circuit, or IC, designed to manage performance of the LED; it acts as the "brains" of the circuit). Based on this, the team established a range of performance specifications that would be relevant to explore for each of the following four elements: (1) solar cell, (2) battery, (3) LED, and (4) external wiring. These four were selected based on whether the element: (a) has a significant effect on overall performance, and (b) is a discrete component that can be substituted in and out of the circuit. Note that the wiring is significant given the low voltage (2 V DC) and length (4 m). Other components, such as the LED driver/IC, also play a large role in overall product performance but are too tightly integrated into the circuit design to enable the substitution of different models with varying performance and pricing. For each element three different values, or "tiers," were identified, and the associated performance and cost characteristics were determined (Table 4). The values tested were based on actual products with performance characteristics within the range deemed viable, based on preliminary testing. Because the function of the circuit is essentially the same for all element combinations, a single function was used to predict performance and cost for each of the 81 (i.e., 3^4) combinations considered (Table 5). Lumen output was normalized across all combinations at 18 lm (which met the performance requirement of >15 lm) so resulting runtimes and costs were the outputs for comparison.

3.3. Calculations

The following relations were employed to calculate product performance:

$$(\text{PV power} - \text{diode loss} - \text{wiring loss}) \times \text{charge eff. of battery} \times \text{daily sun hours} = \text{Watt-hours per day into battery} \quad (1)$$

Table 5
Assumptions and constants.

Assumption	Value
Voltage of PV cell (V_{mp})	2
Charging efficiency of NiMh battery	66%
Daily peak sun hours	5.5
Efficiency of circuit	85%
Nominal voltage of AA battery	1.20

$$\text{Lumen output} = 18\ \text{lm} = \text{power to LED} \times \text{LED efficacy} \quad (2)$$

$$\text{Watt-hours per day into battery} \times \text{circuit efficiency/power to LED} = \text{runtime in hours per day} \quad (3)$$

Note that Eq. (2) was used to normalize all combinations to a set lumen output, designated at 18 lm, by adjusting the amount of power sent to the LED. Clearly, more efficient LEDs use less power to achieve the 18 lm, and therefore were run at lower power. The "power to LED" value was then plugged into Eq. (3) to determine "runtime." For each combination the individual component costs were summed to determine cost-effectiveness for that combination relative to runtime.

3.4. Optimization results

The 81 combinations produced runtimes ranging from 3.0 h to 8.7 h, with 57 of the 81 combinations delivering the minimum requirement of at least 4 h runtime. The combination that ran for 8.7 h cost 63% more than the lowest-cost combination, but provided almost triple the runtime. The results showed that the most cost-effective component to invest in was the LED—extra dollars spent on the LED resulted in better performance gains, all else held constant, than any other tested component. These findings support general energy efficiency theory—given that the LED is the final component in the design, for every efficiency gain to the LED, every component upstream of the LED runs with lower power and current and can often be downsized in performance and cost. The project team used the results from the optimization analysis to select specific models for each of the components tested. Specifically, the team modified the preliminary design to include a higher-efficiency LED, a lower-capacity battery, and optimized resistance for the external wiring.

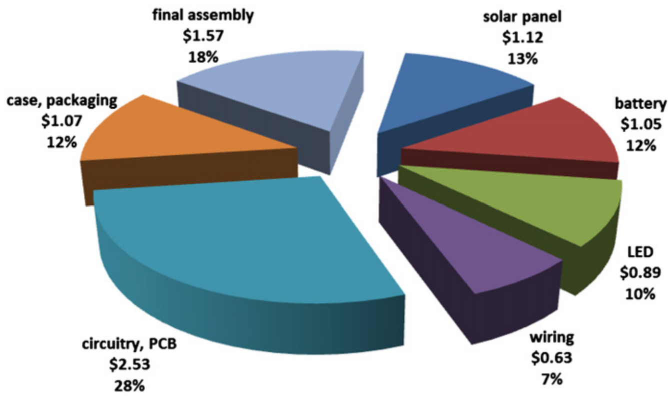


Fig. 3. Cost structure of final design with total cost = $8.86.

4. Cost analysis

4.1. Production costs

The final design was built and tested, and a low-volume (1500 units) initial production run was commissioned. Manufacturing took place in Mainland China in the Shenzhen area, with the costs reflecting standard, non-discounted rates that a new company without industry connections might face. The total unit cost of production was $8.86. Breaking down that cost into the six categories shows that the circuitry comprises approximately 1/4 of total unit production costs (see Fig. 3). Within this category, the highest-cost items were the integrated circuit and switch. The solar panel is the single most expensive component, followed by the LED.

These costs are based on low-volume manufacturing of less than 10,000 units, and there would be significant decreases in pricing for higher quantities. In particular, the cost of assembly—which includes some manual processes, such as soldering wires to the circuit board and preparing packaging—would see large price reductions as volumes increased.

Note that the cost structure of the final light design does not include tooling or set-up costs,[2] only the direct, variable costs of the materials, assembly, and packaging, in effect the "FOB" (free on board) cost of the complete product ready to be shipped. Once shipping, insurance, taxes, and distributor margins are factored in, the retail price may be approximately double, depending on the target market for distribution.

The cost breakdown by category shows some similarities to an LADM industry survey of SPL production costs [10]. Because the categories used in the LADM study do not exactly match with this case study, and the data comprising those categories were not available, it is not possible to provide an apples-to-apples comparison for all components. For example, the LADM study categorizes assembly costs with the case costs, but it is unclear if these are just final assembly, or include PCB assembly. What is apparent is that the median SPL on the market today uses much larger and costlier solar cells, batteries, and LEDs, resulting in a total manufacturing cost of about $19.50 vs. the UC Davis cost of $8.86. This large difference in component size (e.g., a 2.5 W solar cell for industry median vs. 0.5 W for UC Davis) will largely translate into performance gains.

The increase in size and performance is not linear in respect to percentage of overall costs. For example, in the industry median cost structure the solar cell accounts for almost 1/3 of the cost, and the solar panel for almost 1/4 of the cost. That this ratio does not hold when the entire product is scaled down suggests that there is some cost "floor" or minimum costs that are unavoidable even when the performance is scaled down. Some of this could be in the active electronic components—for example, a $0.34 integrated circuit/driver is the minimum needed, whether the solar panel is 5 W and sending high levels of current or the panel is 0.5 W and sending low amounts of current. Most of this minimum cost is likely in the final assembly costs, where the level of skilled labor and the amount of time it takes to solder solar panel leads is similar no matter the size of the panel. Obviously, the higher the volume or quantity of a given product, the lower the assembly costs, and the UC Davis product pricing shown was for very small quantities of 1500 units.

4.2. Production cost projections

The market for off-grid lighting solutions is expected to grow at a significant rate, with one estimate of 40%–65% year-on-year growth in Africa through 2015 [10]. As more organizations enter the market to meet this demand, manufacturing costs will decrease as volumes rise. In addition, global demand for the core technology of SPLs—solar PV and LEDs—will continue to drive improvements in manufacturing and technology advances for those specific components, leading to even lower prices and costs of production. As a result, LADM estimates a 40% overall reduction in manufactured cost for SPLs by 2015, with the majority of that reduction coming from advances in LED technology [10].

In the laboratory, LEDs have broken the 200 lm-per-watt barrier [2], and production LEDs have reached over 150 lm-per-watt. While the top-performing LEDs are likely outside the cost range for most SPLs, these advances in performance drive down costs of lower- and mid-range power LEDs. In terms of the solar cell, global demand will lower prices of mono- and poly-crystalline cells in general, but the small size of the typical SPL solar cell will likely always incur a much higher per-watt price compared to larger SHS-scale or utility-scale solar panels in the 100+ watt range. Perhaps more interesting are developments in amorphous silicon and other types of thin-film PV technology. While less efficient than crystalline forms, thin film is typically much less expensive to produce, and its flexibility and low weight can provide distinct advantages in shipping and distribution.

Bringing SPL manufacturing in-country is often suggested as a way to bring down costs as well as generate local economic benefits. Building the SPL in the country where it is sold would avoid shipping costs as well as import duties, and could provide employment opportunities and tax revenue. Key challenges to this model include lack of skilled technical labor and modern manufacturing equipment in target market countries. Importantly, the local availability of key product materials or components can make a significant difference in manufacturing costs due to import duties and taxes paid on those components. The UC Davis project team experienced this barrier directly when it attempted to develop manufacturing capacity for its SMART Light with a partner in Bangladesh. Because some components were not available in Bangladesh, building in Dhaka would have required importing those components from China or India, paying a high import tariff, and then exporting the complete product to Zambia where it would face additional import duties. For this reason, the UC Davis team moved manufacturing to China, where all components are readily available.

4.3. Customer costs

While this study focuses on costs of production, it is also important to evaluate affordability from the customer's perspective. Key costs for the customer are: upfront cost (first cost, or retail price) and operating costs (running costs). The retail price will be cost of production, plus some combination of shipping, insurance,

[2] The final design incurred approximately $6000 in tooling costs, mostly for the injection mold.

freight forwarding, import duties/tariffs, VAT, distributor margin, retailer margin, and other costs. A common rule of thumb for estimating retail price is to double the cost of production [15,10]. By this measure, the UC Davis SMART Light with a manufactured cost of $8.86 would have a retail price of approximately $18. Given the relatively poor infrastructure and landlocked nature of Zambia, the authors estimate the retail price may be as high as $20. The only real operating cost for the customer is battery replacement. The SMART Light AA battery is expected to last at least 1.5 years, with a replacement cost of approximately $2 (Table 6).

Table 6
Comparison of UC Davis costs vs. industry medians [9].

UC Davis SMART Light			Industry medians		
Solar panel	$1.12	13%	Solar panel	$6.10	31%
Battery	$1.05	12%	Battery	$4.50	23%
LED	$0.89	10%	LED	$3.70	19%
Wiring, circuitry	$3.16	35%	Circuitry	$2.70	14%
Case, packaging	$1.07	12%	Case, assembly	$2.50	13%
Final assembly	$1.57	18%			
Total	**$8.86**	**100%**	**Total**	**$19.50**	**100%**

Since most target customers in Zambia were candle users paying $2–$3 per month for each candle they kept lit, and the product would replace one instance of a candle, a solar portable light with a retail cost of $18 would have a payback period of 6 to 9 months.

To relate the customer's financial costs to actual light output, measured in lumens, there are a number of different metrics used in the literature [13,19,16,11]. The authors used a measurement by Mills and Jacobson [16], "dollars per 1000 lm-h," which expresses the total cost of ownership of a product over its stated lifetime to the amount of useful lighting service produced. With a two-year lifetime the final design delivers light at the rate of $0.34 per 1000 lm-h as shown in Table 7. This compares to $2.18 per 1000 lm-h for a candle and $1.87 per 1000 lm-h for a basic kerosene wick lamp.[3]

Table 7
Inputs for determining cost per unit-of-service for final design.

Metric	Value
Product retail cost	$18
Product lifetime	2 years
Operating cost (battery replacement)	$2
Total cost of ownership	$20
Lifetime light output	52,560 lm-h
Cost per unit-of-service	$0.34 per 1000 lm-h

Assumptions:
1. Battery replacement required after one year, single battery cost is $2.
2. Daily operation is 4 h.
3. Light output is 18 lm.

[3] Using the kerosene lamp burn rate and light output established by Mills [12]. All costs adjusted for Zambia, including prices for kerosene as typically purchased in small quantities with associated markup. Additional assumptions: Kerosene: burn rate=13 l/year, cost of kerosene=$1.50/liter, cost of wicks=$1.42/year, cost of lamp=$1, lifespan of lamp=1 year, luminous flux=8 lm. Candle: burn rate=0.5 candle/day, cost of candle=$0.14, luminous flux=8 lm.

5. Additional findings

5.1. The role of quantity in SPL design

Due to volume pricing, the costs of production for building 1000 SPLs may be 10%–20% higher than the per-unit cost of building 50,000 SPLs. Production quantity will also affect decisions on tooling or production processes. As an example, an injection mold for the plastic case can be machined from steels of various hardness's, with the harder materials costing more to make into molds but lasting longer. If a production quantity is known, then amortizing the capital costs over time can provide guidance for this decision, but this is more difficult for new products without clear estimates of quantity. In terms of production processes, whether to use manual or automated manufacturing depends mostly on quantity, but also on the cost and skill level of available labor, the degree of quality control and uniformity required, the desired impact on employment, and the time available. The project team found that semi-skilled labor for tasks such as assembling circuit boards and manual injection molding of plastic were cost-competitive with automated processes at volumes of only a few thousand units per month.

5.2. SPL adoption also depends on performance, quality, and other non-cost issues

While this article has focused on costs of production and therefore retail price as the key factor in affordability of SPLs, there are clearly many factors that affect adoption and long-term success of the SPL market. User preferences in terms of form factor, features, user interface, and branding, all play significant roles. The market for SPLs and other energy services is diverse, with customers from very different income levels, geographic locations, and cultural norms. Already the market is seeing specialization as manufacturers find and serve niche customer segments, and this trend is likely to continue with more user-centric design [10]. However, even the most well designed product cannot scale without effective distribution. Developing financially and operationally sustainable distribution models appropriate for specific regions may be one of the most important challenges for SPL firms.

5.3. Need for quality control, standards, testing in the SPL market

Because of the pervasiveness of inferior lighting products and market poisoning, quality is a key concern for consumers and manufacturers alike, as savvy consumers are demanding warranties to protect their investments. Respondents to our research in Zambia frequently inquired about the warranty, assuming there would be one and stating they would not consider a purchase without one. There is a large push for the establishment of industry standards and quality assurance programs by LADM in conjunction with the Lumina Project. The latter has established basic performance testing criteria, including measurements of luminous flux, spatial variation of illuminance, frequency of charging as function of desired light per day, and more [16].

6. Conclusion

Through field research and iterative user testing of prototypes in Zambia, it was determined that a solar portable light that could run for at least 4 h a day, and be at least as bright as a simple kerosene lamp or candle, would be acceptable to many users. By simplifying the design and stripping away all non-core functionality, a basic SPL can be manufactured for less than $9 per unit at

low quantities, resulting in a retail price of $18–$20 in Zambia. An optimization study revealed that specifying a higher-efficacy LED reduces the product cost by lowering the power requirements of the PV cell, battery, and wiring. Although smaller SPLs such as in the present study may be marginally less cost-effective compared to larger solar portable lights or solar home systems, the lower initial upfront cost makes them more affordable to the end-user in places where there is limited access to financing. However, for the majority of candle or kerosene users interviewed in Zambia, the product would need to have a retail price below $10, and perhaps $5 for large-scale adoption. This may be possible though increasing production volumes and advances in LED technology.

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